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Assessing the potential for greater solar development in West Texas, USA

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ABSTRACT

As population and economies continue to grow on a global scale, so too does the demand for energy. To improve reliability and independence of energy supplies, the U.S. and many other countries are seeking internally-sourced renewable energy; solar is one such renewable-energy source that meets these criteria. However, all energy sources exert some environmental impacts. In the case of solar, direct impacts stem mostly from alteration of land needed to host infrastructure. Understanding the environmental upside and downside potential of solar energy systems allows a more comprehensive, side-by-side comparison with different energy sources. In this article, we focus on the solar energy potential of West Texas, USA, a large arid to semi-arid region with a rural population and favorable climatic conditions. Texas is an interesting and important region to study given its unregulated and independent grid operation and the additional (and substantial) sources of regionally produced energy. Herein, we assess the geographic and environmental attributes, constraints to (e.g., incoming solar radiation, slope, habitats, ecoregion, water availability, etc.), and the potential environmental impacts on land resources from utility-scale installations of different types of solar energy generation systems. Our assessment points to the balance needed to expand solar energy to gain flexibility in energy sourcing on the one hand, while carefully considering future locations and technology to avoid regional impacts to land and environmental resources.

1. Introduction

As population and economies continue to grow on a global scale, so too does the demand for energy. A rise in worldwide electricity demand of more than 40% is predicted to occur between now and 2050 [1]. Energy demand has historically been met with utilization of fossil fuels (currently at 80% of world demand [2]). To meet the 16-terawatt (TW) demand predicted for 2030, some studies have suggested that an additional 13,000 coal power plants might be needed [3,4], while others predict that the world's energy reserves may expire in as little as 100 years [2]. Compounding this energy dilemma, numerous studies have linked the use of fossil fuels with greenhouse gas (GHG) emissions and global warming [5,6]. In the United States, the Energy Information Administration [7] has reported that electricity contributes 28.4% of U. S. greenhouse gas emissions, with the industrial sector contributing another 22% through nonutility electricity generation and other processes. To improve independence of energy supplies, the U.S. and many other countries are currently seeking renewable energy sources internally that do not contribute to greenhouse gases. Solar is one such renewable-energy source that meets these criteria. Though electricity generation through wind is higher than solar [8], solar energy capacity is increasing substantially, with a technical potential far exceeding total demand for electricity [9].

Many states in the U.S. have established goals to diversify their energy portfolios. In 1999, Texas established its own renewable-generation goal of 5880 MW by 2015 (achieved for all forms of renewable energy) and 10,000 MW by 2025 [13,000 MW of generation have been achieved in 2018 [10]]. Solar installations in Texas have risen quickly over the last few years, with installed-solar capacity in 2017 exceeding 700 MW [11]. In 2019 Facebook announced plans for constructing a 6 square mile solar facility north of Odessa TX [12].

Solar facilities are often located in desert regions with reliably high, incoming solar radiation loads. These regions often have low population densities with minimal pre-existing built infrastructure. However, warm deserts with xeric shrublands, have remarkable levels of biodiversity and fragility, and demonstrably slow recoveries from ecological disturbances [13]. Vasek et al. [14] estimated that disturbance of desert ecosystems without restoration remains for several centuries. Because of the fragility of desert lands, the planning and site selection steps for solar facilities are critical, not only for minimizing negative ecological effects

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associated with the actual site, but also for assessing impacts associated with transmission lines and water withdrawals. The Bureau of Land Management (USA), which administers federally owned lands in six southwestern states (CA, AZ, UT, NV, NM, and CO), has developed action plans to support solar development, identifying approximately 9 million ha of U.S. federal land meeting its strict criteria for development [15].

Landscape management in Texas is unique, with <1.5% of land controlled by the U.S. federal government and the rest owned and managed by private landowners. As such, viable options for solar development in West Texas will be associated almost entirely with the private sector. In this paper, we describe the current status of solar power generation in desert lands, in general, and in West Texas USA, in particular. The goal is to raise awareness of the (mostly) environmental factors that either contribute to, or could be affected by, utility-scale solar power generation facilities in West Texas. It applies the broader experiences of solar power installations in the Mojave Desert of the southwestern U.S. to the Chihuahuan Desert, which has similar vegetation and landscape characteristics.

2. Study area

Our study area was defined by the political boundaries of 18 counties in Texas which contains ~28 million acres (113,310, km^2; Fig. 1). This area encompasses the entire Trans-Pecos region of Texas. The Trans-Pecos region contains the entire Texas portion of the Chihuahuan Desert and the Arizona/New Mexico Mountains ecoregions. Counties east of the Pecos River were included to ensure we captured currently developed utility-scale solar facilities. Areas east of the Pecos River and to the northeast of the Trans-Pecos have historically hosted energy development, particularly oil and gas extraction. However, within the last decade, these areas are also hosting renewable energy development (wind and solar). This is due largely in part to the state's development of Competitive Renewable Energy Zones (CREZ), which bring high voltage electrical transmission capabilities to the region. The proposed McCamey CREZ (Fig. 1) would provide service to parts of West Texas but only to approximately 17% of the West Texas study area. To provide service to regions farther away would require expansion of the proposed CREZ based on a detailed economic analysis.

Approximately 81% of the study area is classified as Chihuahuan Desert, with smaller areas classified as plateau and high plains (Fig. 2 [16]). The Chihuahuan Desert is the largest of the North American deserts, averaging ~24 cm per year of precipitation, usually associated with the North American Monsoon, with precipitation typically occurring during the summer [17]. Available precipitation is defined as the difference between monthly precipitation and potential evapotranspiration (for months in which precipitation exceeds potential evapotranspiration), revealing that West Texas is one of the driest regions (0–5.1 cm per year) in the U.S [18]. The Electric Power Research Institute (EPRI) [19] lists West Texas as having significant areas with a high or extreme water-supply sustainability-risk index.

3. Factors influencing selection of solar power in West Texas

In this section, we present several environmental related factors that could become important in the pre-selection process. These factors are outside of the proximity to power lines or other infrastructure that might alter decision-making. Factors include solar irradiance, land fragmentation and habitat loss, ecological attributes, water resource availability, and environmental microclimates. We also discuss use of brownfields, or those areas already disturbed by energy infrastructure or otherwise degraded.

3.1. Solar irradiance in West Texas

Solar-energy production is linked directly to rates of incoming solar irradiance. In Texas, as in other regions in the world, the amount of solar radiation striking the Earth's surface varies according to numerous factors, including latitude, elevation, aspect, cloud cover, and time of day and year. For generation of electricity to be profitable, solar-energy production facilities need to be situated in areas where solar radiation remains high on a month-to-month basis. Direct, normal, solar resources

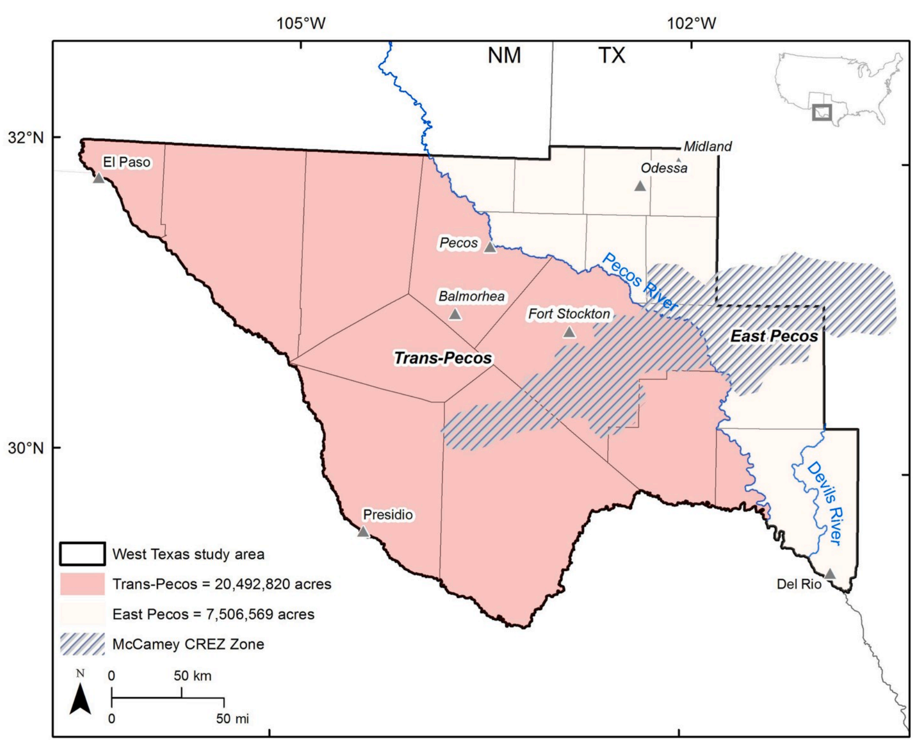

Fig. 1. West Texas study area, including the Trans-Pecos and East Pecos regions, overlaid with the McCamey CREZ zone.

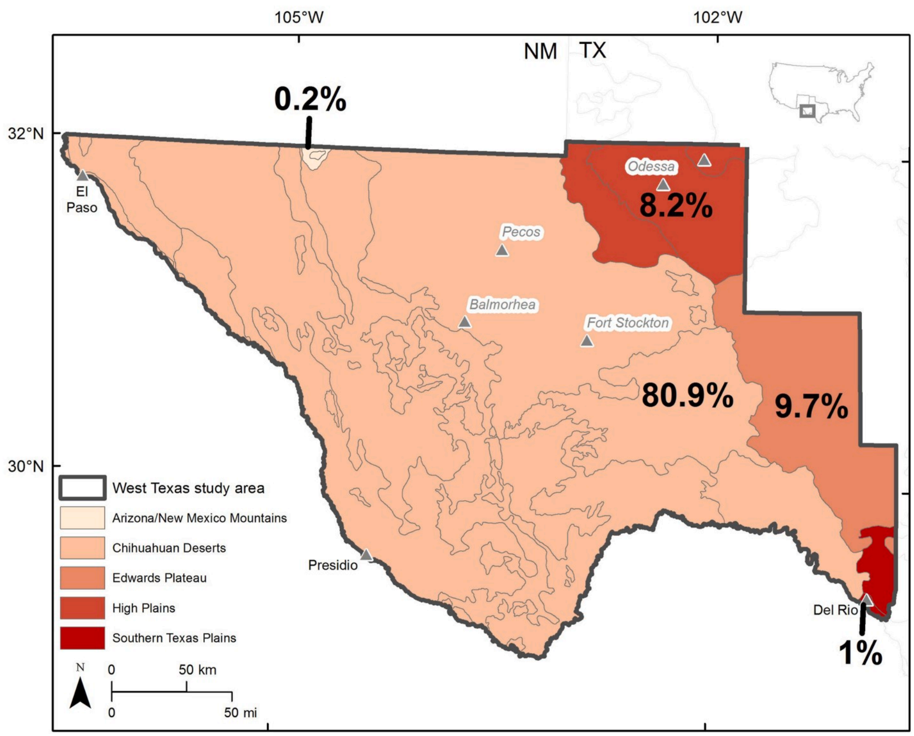

Fig. 2. Omernik Level III ecoregions (Omernik and Griffith [16]) contained within the West Texas study area.

for the state of Texas reveal a well-defined gradient of increasing incoming solar radiation from east to west (Houston 5.0 kWh m^{-2} day^{-1}) with some of the highest values recorded in westernmost regions of Texas (El Paso, 7.5 kWh m^{-2} day^{-1}). Figs. 3 and 4 [20] illustrate areas receiving at least an annual normal irradiance of ≥6 kWh m^{-2} day^{-1} and ≥7 kWh m^{-2} day^{-1}, respectively (6 kWh m^{-2}-day^{-1} level being considered an economic threshold for solar-power production [21]). To estimate area available and suitable for solar PV development, we selected DNI (direct normal irradiance) layers with values > 6.0 kWhm^{-2}day^{-1}, slopes of 5% or less and contiguous areas greater than 32 ha (0.3237 km^2, personal observations Devitt). To estimate area available and suitable for CSP development, we selected DNI layers with values > 7.0 kWh m^{-2}day^{-1} (we selected a higher value because of the higher dollar investment with CSP facilities) that had slopes of 3% or less

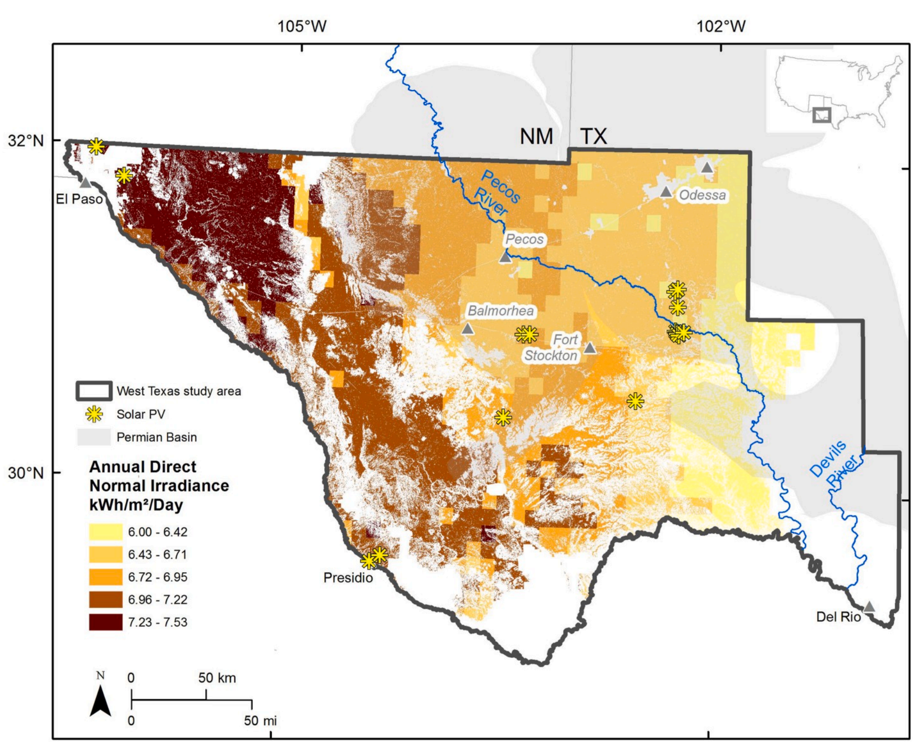

Fig. 3. Annual, direct, normal irradiance in West Texas study area for values ≥ 6.0 kWh m^{-2} day^{-1} (NREL [20]).

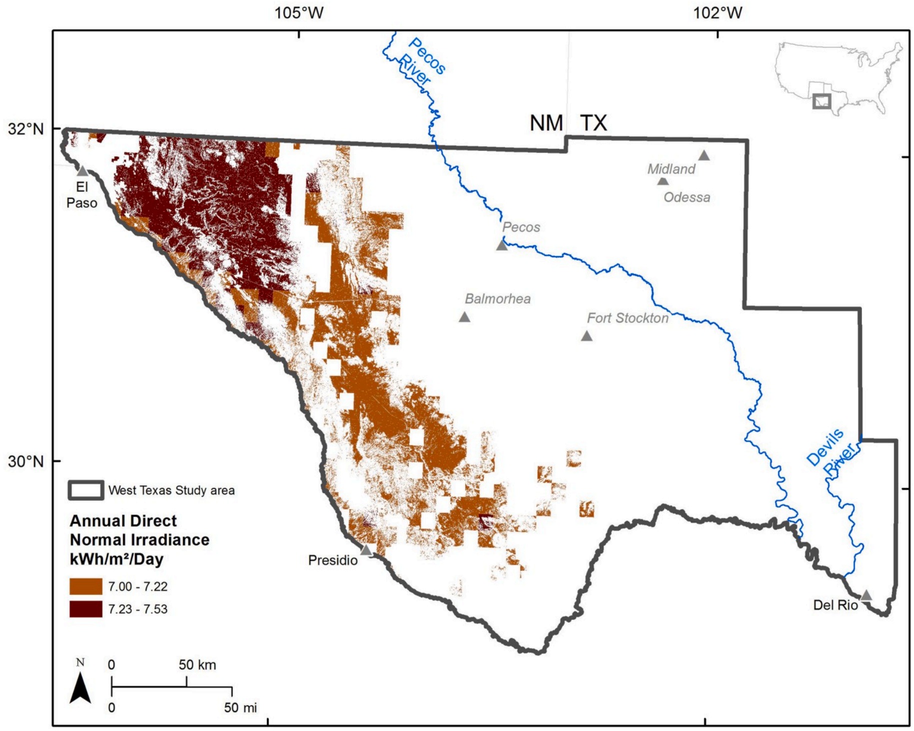

Fig. 4. Annual, direct, normal irradiance in West Texas study area for values $\geq$ 7.0 kWh m^{-2} day^{-1} (NREL [20]).

and were contiguous areas greater than 5 km^2 [22]. Additionally, protected areas (i.e., state parks, wildlife management areas, USFWS critical habitats, etc.), airports and runways, cemeteries, railways, roadways and right-of-ways, waterbodies (i.e., rivers, lakes, streams), and urban areas were excluded as suitable solar-energy development areas (exclusion layers based on [23–33]). In the West Texas study area ~5.4 million ha (48%) meet the 6 kWh m^{-2} day^{-1} threshold, whereas 1.5 million ha (13.2%) meet a 7 kWh m^{-2} day^{-1} value, indicating that significant acreage meets the basic solar irradiance requirement for the placement of solar facilities.

3.2. Land fragmentation and habitat loss

Biodiversity is the variability in life forms within a given area, such as the number of plant and animal species in a habitat or ecosystem, including variation within a species. Because disturbances can impact biodiversity, the number of species that exists in an area before and after a disturbance event is important to know, as is the degree of disturbance of the area (i.e., degraded habitat vs. loss in habitat). As level of disturbance increases, and if the area also undergoes fragmentation (breaking apart of the habitat), the area becomes more vulnerable to invasive species; as some species may not be able to compete successfully to maintain a healthy, stable population. Fahrig [34] stressed the need for not only identifying species vulnerable to habitat loss, but also for estimating minimally required habitat (perhaps a threshold habitat level) to truly understand if differences exist between fragmentation and habitat loss.

With regard to solar-power facilities and their potential to be installed in the West Texas study area, several questions arise: Will the number of species in the area be impacted by installing one to several large, utility-scale solar facilities? If so, how quickly will species be impacted? Will corridors be used to maintain direct connectivity between separated areas to minimize patch isolation and allow for biotic movement? The size, shape, and position in the landscape of these remnant patches also influences biota [35]. As the area becomes fragmented, the ratio of edge:interior will begin to favor edges, which can impact some species significantly because these edges can act as ecological traps [36]. Some bird species have been documented to being drawn to plants along these edges to breed, putting the species at risk for increased nest predation [37,38]. Although some species may be able to travel great distances, they may lack behavioral skills needed to traverse highly fragmented areas, which can effectively become a barrier to movement [35].

Northrup and Wittemyer [39] showed that fragmentation is an unavoidable product of development; therefore, fragmentation is to be expected with solar development. This fragmentation is not only associated with large-scale clearing of an area for the solar facility, but also with placement of transmission lines and roads. These roads can represent barriers to movement, as has been documented for forest mice [40], mule deer and elk [41], and mountain lions [42], depending on the width of the road, traffic intensity, and density of the road network in a given area. Von Seckendorf Hoff and Marlow [43] reported that sightings and signs of the desert tortoise were reduced within 4000 m of roads. We report road density in the West Texas study area in Fig. 5, using a threshold of 6 km/1000 ha, which represents the value reported by Holbrook and Vaughan [44] for wild turkeys in the U.S. associated with increased hunting mortality. As of 2016, less than 1% of the West Texas study area had road densities of <6 km/1000 ha, which may be a high estimate because dirt/gravel roads (especially on private lands) were not included in this assessment. Note that in the high-intensity areas of oil and gas exploration and production, these numbers can change quickly. Although West Texas has a low population density, much of the area already has measurable disturbance based on existing road densities as demonstrated in Fig. 5. Impact on mobility of different fauna in the area is not fully known.

It is also important to recognize possible cascading effects associated with one species impacting other organisms within a given area, such as predator-prey relationships. Such questions need to be addressed during the site-selection process. If construction of a solar facility moves forward, monitoring the health of adjacent habitats will be critical. Change can be slow and subtle, occurring over the life of the solar facility (~30 year), or it can be rapid if more sensitive habitat is degraded. Finally, if

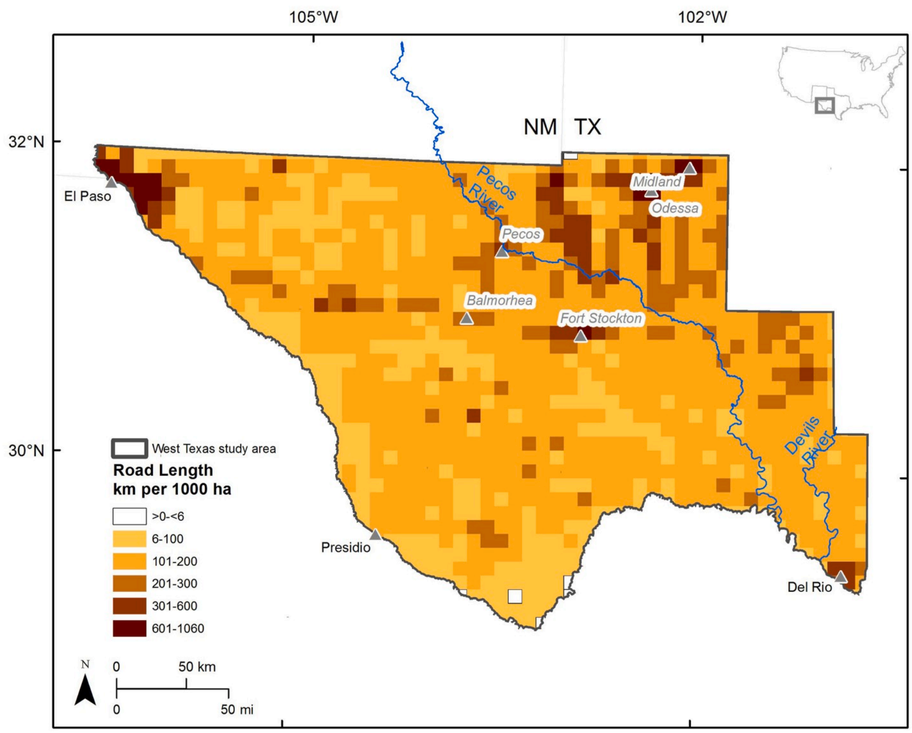

Fig. 5. Road length in km per 1000 ha (TXDOT [29] [30]).

organisms become isolated and impacted by fragmentation and/or habitat loss, how would it impact the gene pool (genetic change) of such organisms, and would some of these organisms be driven to local extinction? These are questions that require attention. In the West Texas study area, which includes the entire Texas portion of the Chihuahuan Desert, this ecoregion provides critical habitat for 415 organisms considered species of greatest conservation need by Texas, 34 federally listed threatened and endangered species, and 2 candidate species under review for federal protection (Fig. 6 [45,46]). Knowing the status of endemic species in a given area is critical in the site selection process for large scale solar facilities. Areas associated with state and federally protected species should be avoided, as they will have lower chances of approval from state and federal regulatory agencies or at best will enter into a delayed and prolonged process.

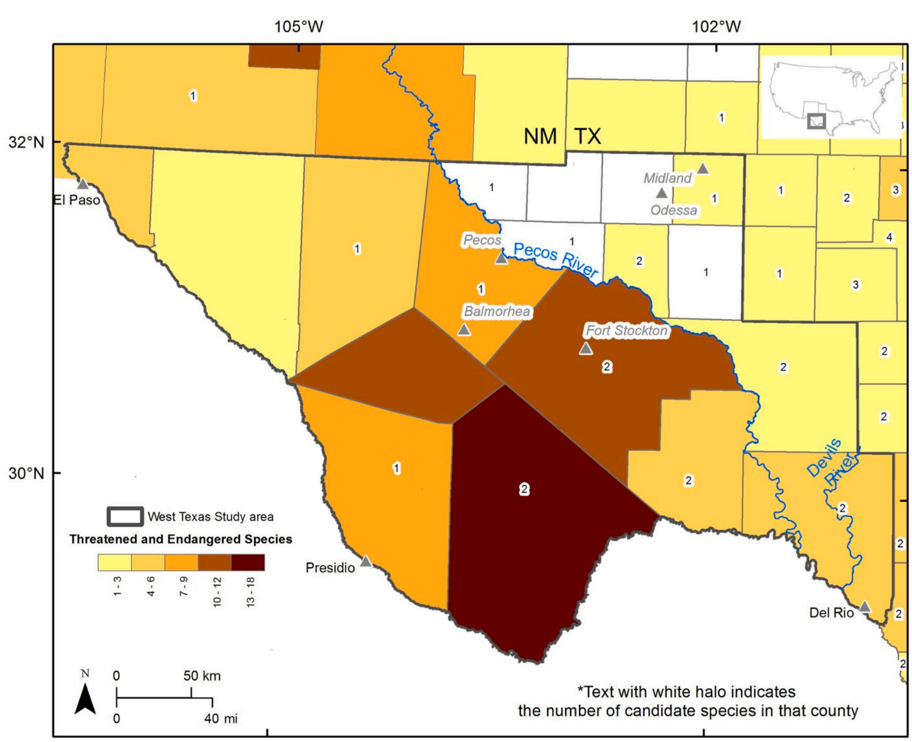

Fig. 6. Federally threatened endangered and candidate species, aggregated at county level. White-haloed text indicates candidate species under review and known to occur in that county (TPWD [45], TXNDD [46]).

3.3. Ecological attributes

Utility-scale solar facilities require significant land footprints. The amount of land needed varies depending on the kind of solar facility developed, solar-energy-capturing efficiency, and whether energy storage occurs at the site, as well as site-specific environmental constraints. The theoretical potential for solar development is therefore often constrained by geographic potential [47]. Hernandez et al. [21] concluded that slope and access to transmission lines had the greatest absolute effect on compatibility of land and technical potential for solar development. Land-area requirements for parabolic troughs, solar towers, and PV have been reported to vary between 0.02 and 0.04 km^2/MW [48]. In the case of the concentrated solar facility in Ivanpah (Mojave Desert, CA), heliostats and towers are located on ~4000 acres (~1600 ha), generating ~400 MW of electricity. Wilshire et al. [49] estimated that, for photovoltaic panels with a 10% conversion efficiency, an area slightly smaller than the state of Maryland would be needed to provide electricity to the entire U.S.; whereas in Australia, Bahadori and Nwaoha [50] estimated that solar energy resources in areas of flat topography within 25 km of existing transmission lines were nearly 500 times greater than annual energy consumption.

Preparing sites for utility-scale PV facilities, workers typically remove vegetation, then level and pack the land, altering drainage networks and surface flow. Roads and transmission lines are also associated with solar facilities and can break up remaining habitat into smaller areas. Sites for solar development should avoid sensitive ecosystems, areas of natural beauty, archaeological sites [51], and areas that would create bottlenecks in terms of geographic constraints on organismal mobility. Because of the increasing demand for energy development in the west, however, McDonald et al. [52] suggested that the outcome might be highly fragmented landscapes represented by energy sprawl. Popcewicz et al. [53] estimated that up to 96 million ha of the five major ecosystems in western North America may be impacted by energy development, with the highest impact projected for shrublands. Within the West Texas study area, 64% of the area is classified as shrubland and 30% as grassland [54] (Fig. 7). If solar development in West Texas accelerates in shrubland areas, complete removal of the plants should and can be avoided, as the majority of this shrubland is of short stature which would require only minor modifications of typical solar panel arrays, allowing significant amounts of shrubland to stay at least in a partially intact state.

Finally, both aquatic insects and aquatic birds have been observed to be influenced directly by the presence of PV solar panels [55–57]. In the case of aquatic insects, Horváth and colleagues [55] noted that they appeared to be attracted more to solar panel arrays than to water bodies—the solar panels in this case being preferred for egg laying, the panels thus acting as an "ecological trap."

3.4. Water availability

Much of the West Texas study area receives an annual precipitation between 28 and 43 cm per year (11 and 17 inches/yr) and is classified as semiarid. However, in the extreme western parts of Texas, annual precipitation can be < 25 cm (10 inches), coupled with a higher potential evapotranspiration rate, classifying the area as arid. Municipalities in West Texas, such as Midland, Alpine, Ft. Stockton, and Pecos, rely on reservoirs and/or groundwater to meet daily water needs. Recent dry periods have demonstrated that growing communities like Midland/

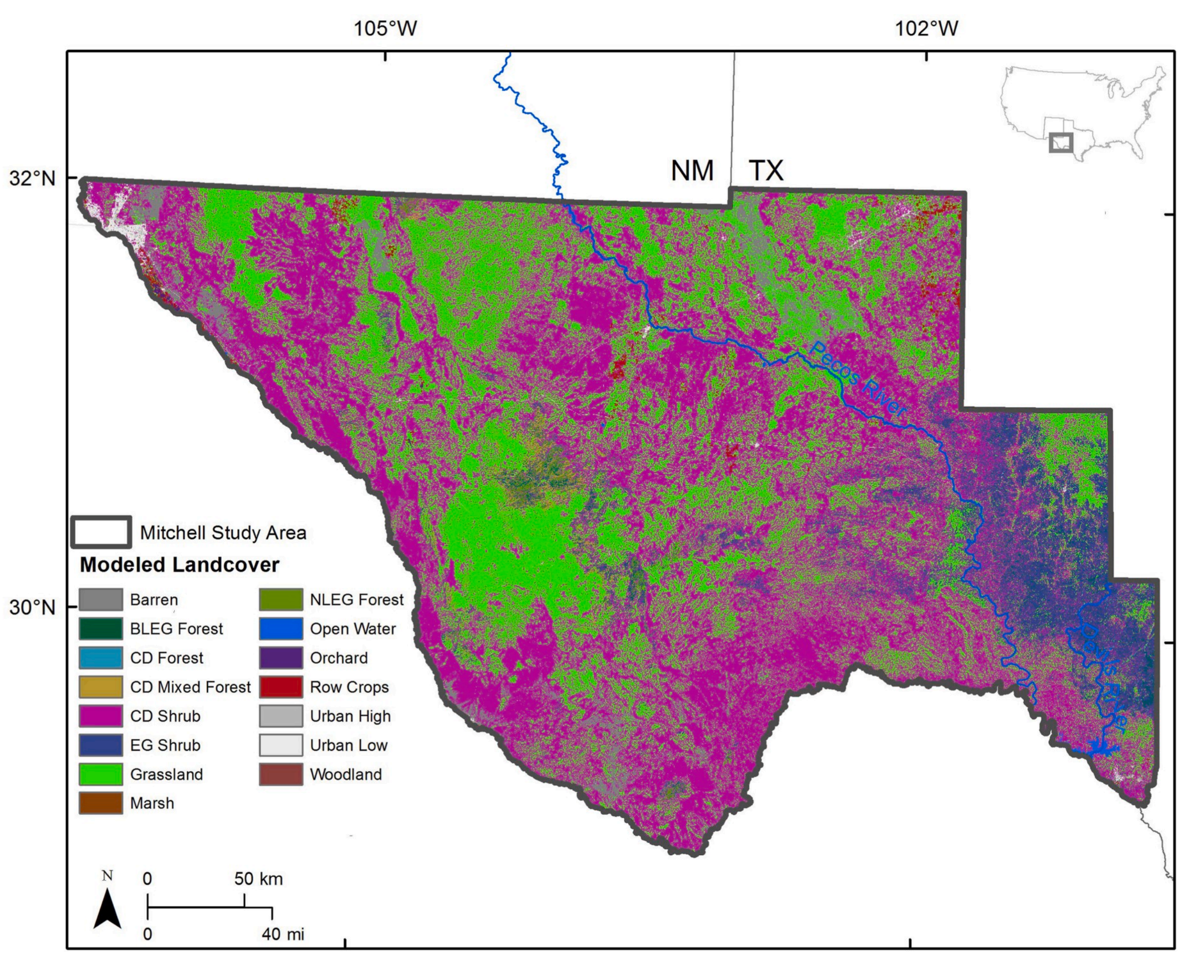

Fig. 7. Landcover types (Elliot et al. [54]) found within the West Texas study area.

Odessa may need to secure additional outside sources of water. For example, a permit in 2017 was granted to a rancher in the Ft. Stockton area to pump ~28,000 acre feet of water per year 100 miles north to Midland (www.oaoa.com/news/government/city of odessa/article). Long-term imbalances between groundwater use and recharge rates threaten ecological and urban systems. Lowering water tables at an unsustainable rate impacts local springs, deep-rooted trees, and shrubs known as *phreatophytes*; leads to possible compaction of aquifer sediments; and, of course, increases the cost of lifting water from greater depths. Groundwater withdrawal in Texas is governed by the rule of capture, regardless of the impact on neighboring wells [58], as long as the water use leads to economic activity. As such, landowners can extract and sell groundwater, regardless of the impact on the hydrologic cycle or the ecological systems that depend on it. In the case of power generation, water consumption for energy production is often defined as the amount of water consumed per megawatt of electricity produced. Fortunately, photovoltaic solar energy requires water only for the cleaning of solar modules. Although loss in PV energy production has been linked at some locations to atmospheric dust deposition driven by both aerosol mass and relative humidity [59], to our knowledge, no studies have documented loss of PV energy production in West Texas from dust accumulation.

Other forms of solar-energy production can use significantly more water. Colmenar-Santos et al. [60] argued that "water conservation is critical to achieve environmental sustainability and should be given priority in a similar way as energy efficiency and GHG reduction policies." Carter and Campbell [61] reported water intensity by fuel source and generation technology, revealing that solar troughs and solar towers consumed >750 gal/MWh, nearly twice that of fossil-fuel technology. Water use for wet-cooled systems is high varying by location. In the case of the 400-MW concentrated-solar-power (CSP) Ivanpah facility located in the Mojave Desert (USA), several thousand acre feet of water per year is needed. Although one such facility might not create a significant water imbalance in a region, constructing large numbers of water-cooled facilities may not be sustainable. The water-sustainability risk index for West Texas is graphed along with areas having normal direct-irradiance values above 7.0 kWh m^{-2} day^{-1} in Fig. 8a [62]. Note the limited locations in the West Texas study area where concentrated solar has high potential based on water and direct solar irradiance, and this potential lessens further if climate projections are considered (Fig. 8b [62]). However it should be noted that both Jeff Davis and Brewster counties are projected to have more precipitation with climate change.

Tarroja et al. [63] warned that water cooled facilities may be forced to end operations if water shortages become a reality and contingency plans must be established to avoid such outcomes. Contingency plans can include streamlining water use and, possibly, converting to a dry-cooling system. Such decisions must be part of management efforts to achieve sustainability and should be part of the initial management plans as well, before technology and site selection are made. As such, concentrated solar with wet cooling in this region would need to be closely evaluated.

Dry-cooled systems, now being used at some sites in the U.S., blow air over extensive networks of steam pipes equipped with convective cooling fins to dissipate heat. Unfortunately, the low heat capacity of air compared to water reduces efficiency of dry cooling [64]. For example, Klein and Rubin [65] conducted a life-cycle assessment for concentrated solar-power plants with different energy-backup systems and reported a 72–78% lower water consumption with dry-cooling systems. They encouraged future studies of dry cooling using parabolic-trough plants, noting reduced onsite water use by up to 93% in desert regions, without significant increase of greenhouse-gas emissions or land use.

Constructing large-scale solar facilities could lead to significant, negative ecological effects from disruption of surface-water flow patterns unless washes and vegetation are left intact [66]. Solar facilities, along with roads and transmission lines, can concentrate water drainage and produce larger and higher energy water flow [67], leading to onsite erosion damage and scouring of deeper washes in downgradient locations (Devitt, personal observation). From a habitat perspective, altering surface hydrology could impact sediments, nutrients/minerals, and organic matter being transported downgradient [48]. Potter [68] noted that normalized-difference-vegetation-index (NDVI) change associated with solar-energy development could be attributed to water-flow pathways through canyons and desert washes. In regions with aquatic ecosystems, this diversion and loss in surface water flow could lead to the drying of ephemeral water bodies [48] and alteration of ecosystems that rely on this extra flow.

3.5. Microclimate

Large solar developments (i.e., at the km^2 scale) can alter the albedo, vegetation cover, and energy balances within facilities. The larger these solar developments become, the more significant the impact on energy-balance shifts, especially in terms of the release of short and longwave radiation. Barron-Gafford et al. [69] suggested that panels may be altering release of longwave radiation, preventing the soil from cooling as much as it would without panels. Approximately 63% of incoming solar radiation is transmitted through the panels [70], where the underlying surface temperature can be 10 °C higher than the absorbing

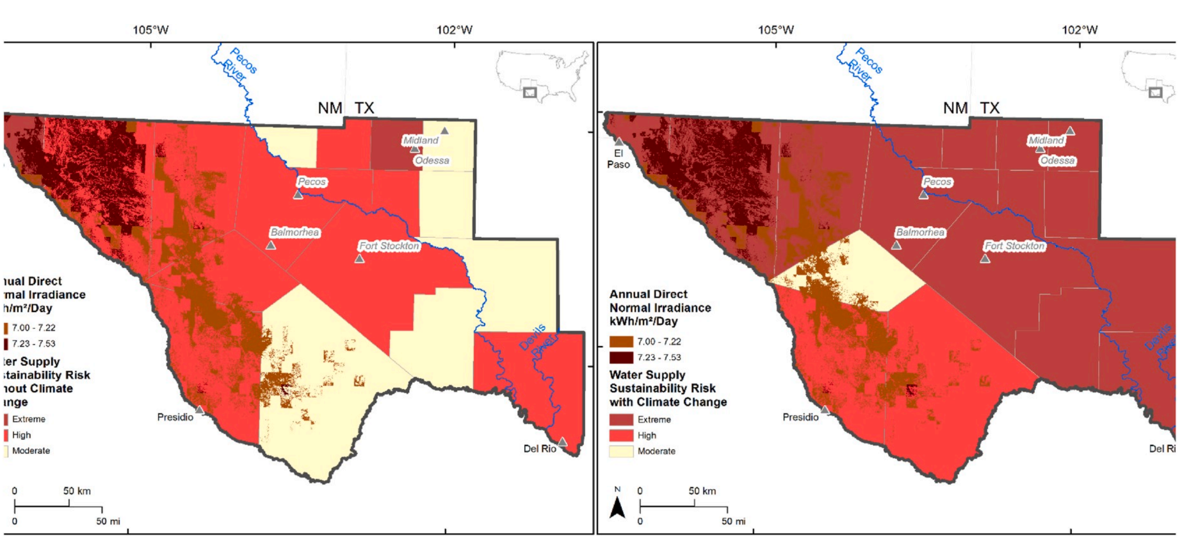

Fig. 8. Water-supply-sustainability risk index and annual direct, normal irradiance without (a) and with (b) climate-change adjustments (Spencer and Altman [62]).

face of the panel, which can in turn exceed ambient temperatures by 15–20 °C (Devitt, unpublished data). Barron-Gafford et al. [69] reported that daytime air temperatures are 3–4 °C higher over a PV plant in Arizona than over adjacent wildlands at night. Because the solar facility was without vegetation, a higher amount of sensible heat was stored in the soil, leading to higher release at night. By comparison, Fthenakis and Yu [71] reported elevated (by 1.9 °C) air temperatures above the center of a PV facility in New York compared to ambient temperature, with temperatures along a 300-m gradient remaining 0.3 °C above ambient. They indicated that the solar array cooled completely at night, suggesting little if any heat-island effect.

Because solar panels can stand a meter or more above the height of shrubland vegetation, panels and extended arrays will alter roughness length and turbulence, accelerating heat movement and water loss via transpiration in adjacent plant communities. In Nevada, (Devitt, ongoing research) with vegetation similar to West Texas, air temperatures at a 1 m height and downgradient from a 1 km^2 PV facility were observed to be as much as 3–5 °C warmer than air temperatures measured within the upgradient edge of the facility (representing a clear heat-island effect that extended as much as 400 m into the plant community). These higher temperatures were observed primarily during early morning hours and during cooler months. The biological significance of this rise in temperature remains under investigation; however, increased soil temperatures are known to accelerate microbial respiration [72] and change growing-season length, altering carbon cycling. Increasing conversion efficiencies of solar panels and/or increasing albedo can alter how heat is dissipated and the extent that heat is moved off the panels and the facility. However, allowing plants to grow within panel-array areas could provide different levels of shade and reduce photo damage and possibly enhance photosynthesis, growth, and plant-water status—all altering the energy balance and extent to which heat buildup and heat transfer occur (known as *overall cooling effect*). Although less CO_2 would be produced with solar-energy production than other energy technologies, the actual reduction might be less than expected because carbon-storage capacity will be reduced in the clearing of vegetation for site development [73]. Moving forward with solar development in West Texas can be a more eco-friendly energy option if vegetation and wash systems can be maintained within the facilities, lessening heat movement, sequestering greater amounts of CO_2 and providing functional habitats.

3.6. Use of brownfield sites

Cameron et al. [74] stressed that areas should be selected that are both (1) suitable for renewable-energy development, and (2) of relatively low biodiversity-conservation value. In the case of the Permian Basin in West Texas, which represents 42% of the West Texas study area (Fig. 1 [75]), fossil energy development for nearly a century has led to ~184,000 permitted wells [76], including oil- and gas-producing, support, and abandoned wells. Some of these areas containing multiple well pads, with wells no longer in production, would be suitable sites for solar development, given that the habitat is already in a degraded state. Such sites are often referred to as "brownfield sites," defined herein as a former industrial site where future use is influenced by environmental contamination. Compared with coal-based energy generation, Fthenakis and Kim [77] reported that a PV fuel cycle with 13% efficiency in conversion and insolation of 2400 kWh/m^2/yr would generate, on average, 40% more electricity than from a coal-fuel cycle, given the same area of land. In addition, PV would not require reclaiming mine lands or accessing additional lands for the disposal of waste. Utilizing brownfield sites in West Texas would allow Texas to further diversify its energy portfolio while minimizing damage to intact ecosystems found elsewhere in the region. However, it should be noted that the International Renewable Energy Agency [78] estimates that by 2050, solar-panel waste may grow to 78 million metric tons.

4. Recommendations regarding solar development in West Texas

A paradigm shift is needed in how large-scale solar facilities are located and built—one that merges engineering and biological solutions, protecting solar infrastructure while also ensuring wash-flow connectivity. Grippo et al. [48] highlighted the need for this balance as even construction of a road can significantly truncate the upgradient collection of rainwater. In southern Nevada, for example, midday leaf xylem water potentials (internal plant water status) of creosote shrubs growing within the first 400 m downgradient from a 2.6-km^2 PV facility were extremely negative (−7.0 MPa) when compared with those of plants growing 1000 m downgradient (−3.5 MPa) (Devitt, current research in progress). This difference appears to be closely associated with the decoupling of surface hydrology and rainwater harvesting. Croke et al. [79] pointed out that disruption of these surface flow networks is often nonlinear and becomes an altered process at larger scales. The following are specific recommendations associated with possible solar development in West Texas:

1) Focus future expansion of solar on brownfields. Work with landowners to identify existing brownfields for solar development, which may require working with multiple landowners. Special emphasis should be placed on areas containing inactive oil and gas fields and areas with major transmission lines and pipelines.
2) Educate energy companies and landowners about the ecological value of constructing solar facilities that leave native vegetation and surface washes intact within the facility to maintain habitat, even if in an altered state.
3) A cost benefit analysis should be done justifying large scale conversion of desert ecosystems for energy development. This would require quantifying the value of intact ecosystems (monetary terms). As ecosystems are modified and reduced in size, a true cost benefit analysis would balance the costs of these modifications and reductions against the benefits of energy generation. Assigning monetary value to ecosystems services is a significant undertaking, especially when large regional areas are being considered. Readers are referred to the recent work of McClung et al. [80].
4) Encourage landowners to develop and implement mitigation plans jointly with energy companies that restore lands and ecosystems, not only after the initial construction phase is complete, but also after the decommissioning of the facility, which may occur decades later.
5) Encourage photovoltaic and in the case of concentrated forms of thermal solar, only those that are dry cooled. This is particularly relevant for West Texas where the water sustainability risk index is high.
6) Avoid solar development in areas with high conservation value. Conduct thorough site reviews assessing biodiversity. Landowners need to be well informed of tradeoffs and potential damage to desert ecosystems associated with utility-scale PV facilities.
7) Ensure that site selection and design of facilities are based on avoidance of sensitive habitat and minimization of fragmentation, by providing connectivity corridors to allow for flow of organisms between subpopulations. This step requires working closely with ecologists for input during the design phase of any project.
8) Install fencing with openings to allow small animals to move freely into and out of solar facilities.
9) Develop regional plans to interconnect dispersed, naturally variable sources of energy, such as wind and solar [81]).
10) Expand weather forecasting to better manage the grid; cloud cover and storm systems can decrease solar production

dramatically. Develop strong ties with Texas universities to address this issue.

11) Educate the public about peak energy demand, recognizing that solar can play an important role in meeting daytime peak energy demands. Educational outreach through the Texas Cooperative Extension Service is suggested.

Acknowledgements

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